NEWTON Deliverable D2.3

Updated requirements and objectives for long-term scenarios

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Abstract: NEWTON brings significant technological advances in the field of magnetometry by means of developing a new portable and compact multi-sensor instrument for non-invasive in-situ magnetic characterization of rocks from planetary surfaces and sub-surfaces. This innovation widely opens a new via in the understanding of some of the next objectives related to the Solar System exploration roadmap. This document reviews the requirements and objectives with the aim that NEWTON instrument could take part in future long-term space exploration programs which target to a better understanding of the origin as well as the geological and magnetization history of the celestial bodies. Within this general vision, NEWTON instrument can be part of modular multi-instrument suites in order to perform a complete in-situ surface characterization. The exploration of the Moon and Mars have been always the main objectives of NEWTON project, however in the context of this these more extended future multi-sensor instrument application, the innovation provided by NEWTON instrument can be also applied to the characterization of other celestial bodies such as asteroids.

Keyword list: Planetary Science, magnetometry, mineralogy, geology, complex susceptibility, multi-sensor system, Mars, Moon, asteroids, signal processing, susceptometer, magnetometer, magnetic amplifier, magnetic mapping, terrestrial analogues, ESA, NASA, space exploration.

Executive Summary

NEWTON instrument is developed to provide a significantly improved future characterization of the mineralogical, geological and geophysical properties of surface rocks of terrestrial planets, moons and rocky asteroids. In the previous report D2.2 delivered in April 2018 we have presented the State of the Art concerning the geological exploration of the Moon and Mars with special emphasis on the requirements and use of NEWTON instrument as important geophysical exploration tool. This new report D2.3 concerns the requirements and objectives with respect to long-term exploration scenarios after the end of NEWTON project. We include some most recent publications related to magnetic and geological aspects of such celestial bodies and we are now also considering asteroids as potential sites for a future in-situ surface exploration with NEWTON instrument.

Future long-term space exploration programs and the possible opportunities to include our multi-sensor instrument have been revised. The aims of future space missions' programs concern a better understanding of the origin and geological history of the celestial bodies as well as their magnetization histories with related shielding effects and the exploration of extraterrestrial volatile and water resources. Future missions will also investigate elemental enrichment processes and related formation of extraterrestrial resources and ore deposits. Within a general vision of future space exploration, we suggest the use of modular multi-instrument suites for a relatively complete in-situ surface characterization. We argue that NEWTON instrument should be included within such analytical packages to provide also in-situ measurements of the magnetic remanence as well as distinct magnetic susceptibilities, since these geophysical characteristics represent an important tool in the context of the above described exploration topics.

In this report we also present examples and first results of NEWTON instrument application. With this work the team aims to be prepared for future extraterrestrial missions at an early stage and to increase our long-lasting experience in technological development as well as practical training and scientific research applications. In the context of more extended future multi-instrument applications, NEWTON instrument was tested on many distinct crustal analog rock suites for which we describe and illustrate first results in this report. The general aim of the practical work was to improve our data interpretation within the possible extraterrestrial mineralogical and geological scenarios and to proof its capacity for geophysical exploration. During the practical field work the capacity and potential to become integrated within future modular analytical systems have been also tested. The presented very successful case studies include (1) magnetic mapping of a volcanic crater of the Pali Aike Volcanic field in Chile with unusual high magnetic anomalies and to explore their origin (2) magnetic surveys of basaltic craters on Lanzarote island to proof how common are such pronounced magnetic anomalies of volcanic craters, (3) investigation of the origin of crater-like structures on basalt plains, based on magnetic, morphological and mineralogical constrains, (4) tests concerning the capacity of NEWTON instrument to differentiate geological units with very low magnetic contrast and (5) to trace and map hydrothermal ore-bearing mineralization.

Further two chapters of this report concern the improvement of modelling of orbital remote sensing magnetic data for an advanced surface rock characterization of celestial bodies and its implication for a better landing site selection. These studies have been partly performed in the context of NEWTON project. They are also important for the definition of aims and more detailed planning of future space exploration missions. Finally we include a chapter concerning updated technical specifications for NEWTON instrument which is based on the review of the geological and geophysical State of the Art as well as our practical test and implication from modelling results.

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Abbreviations

AC	Alternating Current
AMR	Anisotropic Magneto Resistance
CLPS	Commercial Lunar Payload Services
CNRS	French National Scientific Research Centre
CONDOR	COmet Nucleus Dust and Organics Return
CORSAIR	Comet Rendezvous Sample Acquisition Investigation and Return
COTS	Commercial Off-The Shelf
DC	Direct Current
ESA	European Space Agency
EU	European Union
ExoMars	Exobiology on Mars
FM	Flight Model
INTA	Spanish National Institute of Aerospace Technology
ISECG	International Space Exploration Coordination Group
JAXA	Japan Aerospace Exploration Agency
LUVMI	LUnar Volatiles Mobile Instrumentation
MASCOT	Mobile Asteroid Scout
MAVEN	Mars Atmosphere and Volatile Evolution mission
MGS	Mars Global Surveyor
NASA	National Aeronautics and Space Administration
NETSSEM	Network of Small Satellites for the Exploration of Planetary Magnetosphere
NEWTON	NEW portable multi-sensor scienTific instrument for non-invasive ON-site characterization of rock from planetary surface and sub-surfaces
TRL	Technology Readiness Level
TTI	Information and Communication Technologies
UPM	Technical University of Madrid
US	United States
UT	University of Trier

1. INTRODUCTION

NEWTON instrument is specifically developed and designed to provide a significantly improved future characterization of the mineralogical, geological and geophysical properties of surface rocks of terrestrial planets, moons and rocky asteroids. On a long-term perspective after the end of NEWTON project we propose and expect that NEWTON instrument could form an important part of future multiple and modular instrument suites which will provide a more extended rock characterization and detailed is-situ mapping of surface rock properties of celestial bodies. Such future missions beyond 2020 have been partly reviewed in the D2.2 report delivered in April 2018 and are also updated in this recount. Many of the upcoming missions will include compact multi-instrumental suites for a more detailed and partly high resolution surface rock mapping. The capacities of such improved future exploration tools have been recently demonstrated by the Mobile Asteroid Scout (MASCOT) which is a small lander on board the Hayabusa2 mission of the Japan Aerospace Exploration Agency to the asteroid 162173 Ryugu (e.g. Hercik et al. 2017, Jaumann et al. 2017). Future space missions aim a better understanding of (1) the origin and geological history of celestial bodies as well as their magnetization histories with related shielding effects (Lühr et al. 2018), (2) exploration of extraterrestrial volatile and water resources (e.g. Cleeves et al 2015) which can be used during future missions and (3) investigation of elemental enrichment processes and related formation of extraterrestrial resources and ore deposits. However, recent multi-instrument suites do not provide devices to measure magnetic susceptibilities, which represent an important tool in the context of the previously described exploration aims. To accomplish the former topics, NEWTON sensor should be also part of the instrumental suite to provide a detailed characterization of rock composition at future landing suites and surrounding areas by e.g. rover or robotic mapping. In particular, the potential regional magnetic shielding, due to a remanent magnetic rock behavior, must be estimated with respect to possible past life formation as well as future habitability. Furthermore, such local to regional mineralogical and geophysical rock characterization will be important to detect and consider the potential of extraterrestrial raw materials and ore deposits.

To be prepared for future extraterrestrial missions, and in the context of more extended future multi-instrument applications, we are testing our equipment on many distinct crustal analog rock suites to improve our data interpretation within the possible mineralogical and geological context and to proof its capacity for geophysical exploration in the context of long-term extraterrestrial missions. During our on-going practical field work we are also testing the capacity and potential to become integrated within future modular analytical systems. This includes estimates on the sensitivity limits for rock determination at low magnetic contrast as well as with respect to natural and artificial magnetic noise, and tests with respect to the technological compatibility with other instruments. The synchronization of data acquisition from the distinct magnetic sensors as well as a synchronous control of attitude and positioning is also tested during the field work by using distinct hard and soft ware configurations.

Our field studies also aim to provide a more improved analytical rock characterization as it may be available by future extraterrestrial multi-sensor instrument suites. Therefore our distinct magnetic field work data are validated and interpreted within an extended compilation of mineralogical and geophysical data, obtained by our own laboratory characterizations (e.g. magnetic carriers) at INTA and UT. For these studies we have also integrated and considered published data from the investigated geological units for an improved interpretation of the magnetic data in the context of its geological history. The new results obtained during our field campaigns are currently under preparation and will be submitted this year for publishing to International Scientific Journals (Kilian et al. 2018; Diaz-Michelena et al. 2018).

We are convinced that our technological and practical experiences with NEWON instrument represent an important perception in the definition of the scientific goals of future missions. In the context of long-term future exploration scenarios we are trying to convince the scientific community that our multi-sensor magnetic equipment should be considered as important future exploration tool.

2. LONG-TERM SCENARIOS AND NEW EXPLORATION HORIZONS

When dealing with missions related to planetary exploration, scientists have to face very long-term mission scenarios and must provide long-term experiences concerning the analytical approach and related data handling and interpretations. In the D2.2 document delivered in April 2018, we gave an update on the short-term exploration scenarios, for which proposal calls are partly still on its way. Since the delivery of the D2.2 document, the M5 mission selection was performed by ESA while the DePhine proposal with proposed magnetic studies of the Martian moons Phobos and Deimos was unfortunately not selected.

Many missions and scientific goals of the next decade are still not well defined and related calls pending, since scientific arguments have often to cope with other issues, such as political decision and economic situation. However, NEWTON project's members intent to be well prepared concerning technological as well as scientific know-how, to contribute in the context of long-term exploration scenarios. Thus, this report documents our preparation and scientific visions with regard to long-term exploration scenarios.

Among the long-term future missions there are in particular three classes of NASA exploration programs:

1. **Discovery missions** (cost 600-700 million dollars, low cost), which concern the testing and use of new space technologies and applications. Each mission works together with industry to transfer technologies used in the mission, especially those that enhance science acquisition and reduce cost.
2. **New Frontiers missions** (cost up to 1 billion dollars)
3. **Flagship missions** (cost 1-2 billion dollars): host a wide range of instruments for in-depth studies.

2.1. Mars

Beyond the currently available plans (see D2.2), there is very little known about future Mars exploration. The general perspective is to send humans to Mars at some time in the future. This implies many preparatory missions, with specific objectives. On the NASA side, these missions are developed by the Human Exploration and Operations Mission Directorate, and by the Space Technology Mission Directorate. Amongst the scientific objectives there is the exploration of in-situ resources (such as water, or ore), life sustainability, and feasibility of a long-term settlement. On the ESA side, the post ExoMars exploration program is uncertain, but since there have been many collaborations between ESA and NASA, they will probably continue.

One of the intermediate steps to land humans on Mars is the so called 'lunar gateway'. It is described below in chapter 2.2 which highlights the Moon exploration as an important future mission scenario with forthcoming calls of opportunities for instruments similar to NEWTON.

Despite the fact that there does not seem to be any near future mission to Mars provided with lander in order to offer NEWTON instrument for a technology demonstration in a relevant environment and to improve scientific results, some members of the consortium are currently participating in the definition of other missions to dig in the knowledge of the magnetic features of Mars. This is the case of NETSSEM proposal as an answer to ESA call Class F - Phase 1. NETSSEM intends to build a NETWORK of SMALL SATELLITES for the EXPLORATION of MARS MAGNETOSPHERE.

The mission does not foresee any lander since it is mainly devoted to the study of the Martian space environment reaction to external perturbation (either solar or interplanetary) through the characterization of the magnetosphere. However, it will shed light on the formation of the hybrid magnetosphere and this is indirectly related to the ancient dynamo, and therefore stated here as one of the long-term scenarios for the consortium.

Of interest could be also a Chinese mission to Mars which was officially approved in January 2016. It will be launched in summer 2020 and should arrive at Mars in early spring 2021. With a further developed landing technology inherited from CE 3 (Chang'E 3 mission, launched in 2013), the mission consists of an orbiter and a rover. The orbiter will also have plasma analyzers on board for measuring the surface magnetic field along the rover's trajectory which should provide important magnetic field measurements directly on the Martian surface. China is also planning a Mars sample-return mission which will probably be launched around 2030 (Wei et al. 2018).

2.2. Moon

In May 2018, NASA confirmed its intention to return to the Moon, as stated in its Space Policy Directive 1, "*Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations*." This very ambitious program covers several aspects. One of them is to have a robotic exploration of the lunar surface in order to characterize possible resources to be later exploited. These in-situ objectives will be pursued in parallel to the implementation of the lunar gateway (FIGURE 1) an exploration and science outpost which would be deployed in orbit around the Moon.

In terms of surface exploration, we believe that NEWTON could be part of a typical payload for in-situ rock characterizations. NEWTON instrument prototypes 1 and 3 are being developed with special performances for planetary exploration, which means that resolution and characteristics are very suitable for natural rocks. They will have the capability to determine magnetic susceptibility of Lunar and Martian rocks in a wide dynamic range. Either for light rover platforms, high capacity rovers with portable laboratories or hand-held devices that astronauts could easily carry and manipulate. Thus NEWTON instrument is able to improve the in-situ characterization of the magnetic environment in a LUNAR robotic or manned mission.

In this frame, NASA recently issued a formal solicitation for 'Lunar Surface Instrument and Technology Payloads'. The goal is to look for possible experiments to fly around or to land on the Moon. As stated in the call, "*This call is specifically geared towards small payloads that can be ready quickly in order to meet the immediate need for payloads for early CLPS flights. We are interested in flight spares, engineering models, modified off-the-shelf payloads, student hardware or any other hardware that can credibly meet the aggressive timeline outlined below.*"

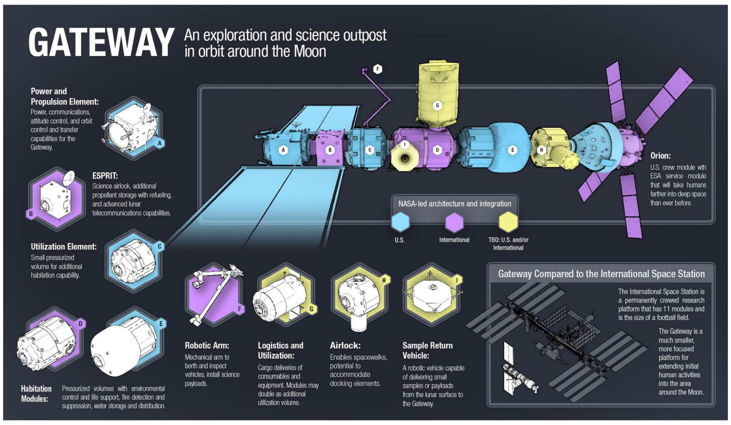

FIGURE 1. Description of the lunar gateway exploration program (credits NASA).

This is indeed a very short schedule, as outlined in the TABLE 1 below. The first answer to this call is due on Nov. 19th for the first step, and Jan. 17th for the second step. It is also stated that 'Proposals from Non-US Organizations will not be accepted. However, international participation is welcome as team members or hardware providers on a no-exchange of funds basis. There is no limitation on percentage of foreign participation'. So any NEWTON related proposal will have to be done with US collaboration.

TABLE 1. National lunar US mission timeline, as found in the Lunar Surface Instrument and Technology Payloads solicitation document.

Payload Milestone	Milestone Date
Payload Delivery to Commercial Lander Provider	March, 2020-Dec, 2021
Payload Integration Complete	Delivery + 3 months
Lunar Lander Launch Date	Delivery + 5 months
Lunar Lander Achieves Lunar Orbit	Launch + 15 days
Lunar Surface Touchdown (LST)	Launch + 30 days
Lunar Surface Mission Complete	LST + 7 days
Data delivered to PDS	End of Mission + 6 months

Although it is obviously a too short time frame for NEWTON while it is in its development phase, it is likely that there will be later (similar) calls, beyond 2021. For expected call of this opportunity NEWTON should be (at least) TRL 6. In order to reach such TRL and for increasing the chances of NEWTON to be included in a lunar exploration mission, the NEWTON team has looked for synergies with other European space oriented projects. During the NEWTON workshop, held at INTA from 22nd to 24th October 2018, our team has discussed with LUMVI project (Horizon 2020 grant agreement 727220) representatives the possibilities to include NEWTON magnetic susceptometer as payload. During the workshop and after brief technical analysis, such integration revealed feasible without evident limitations, due to the compact size, and low energy demand of NEWTON. Even more, LUMVI representative pointed out the interest of LUMVI in NEWTON concept of instrumentation for lunar geophysical research.

A scheme of a possible distribution of the different units of NEWTON prototype and the position on the LUVMI rover platform during integration is depicted on the following image:

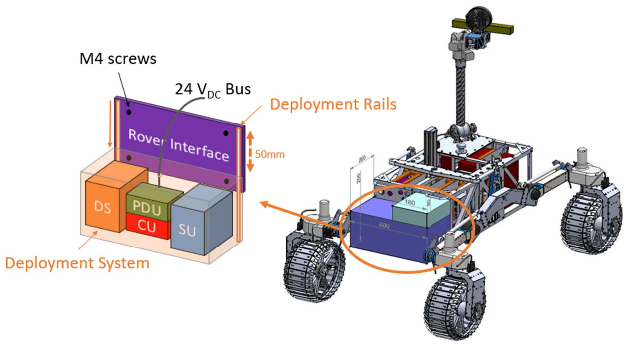

FIGURE 2. Scheme for integration of NEWTON instrument with rover system for lunar exploration (LUVMI).

Besides NASA, ESA is also preparing a new European Space Program. It is not yet finalized, and no details are currently available. A first hint may be the recently announced F-call, for small-scale missions or payloads to be launched as piggy-bag of the other L or M missions (therefore sharing and mutualizing launch costs). This first F-call had a due date on October 25th 2018 for letter of intents. The next Cosmic Vision program, '2050', is also under preparation. Europe shall to return to the Moon and later to Mars, within international collaborations.

Intensive future lunar robotic exploration will concentrate on Polar Regions (by NASA, ESA, JAXA) since remote sensing data suggested possible valuable resources of volatiles or even water (Inoue et al. 2018)

NASA:

> *New Frontiers:*
>
> Moonrise sample return mission. The Moonrise lander would touch down within the South Pole-Aitken Basin.

CHINA:

Chang'E 4 is designed to land on the far side of the moon in 2018, and the first sample-return mission, Change'E 5, is expected to bring back about 2 kg of lunar soil from the near side of the moon in 2019. It is likely that these two CE missions may be delayed for a short time due to the schedule of the Long March 5 rocket.

Although not yet fully determined, China is also planning three possible missions to the Moon's South Pole. The future Lunar missions are expected to resolve the structure and composition of the lunar deep interior, reveal the mechanisms of magma ocean crystallization and crust–mantle differentiation, and provide direct evidence of the presence of water (ice) on the Moon (and its origin) (Wei et al. 2018)

2.3. Asteroids

The innovation provided by NEWTON technology in terms of magnetometric surveys could be also applied to the exploration of other celestial bodies such as asteroids. In this new scenario NEWTON could be part of an advanced suite of instruments which allows the characterization of these planetary bodies.

The International Space Exploration Coordination Group (ISECG) consists in a forum set of the most relevant space agencies around the world. The last edition of their Global Exploration Roadmap (ISECG, 2018) has been published in January 2018. It documents the ambitious goals of agencies roadmaps concerning the expanding human presence into the Solar System including particularly surface explorations on Mars and the Moon. Preparatory missions include robotic missions to both celestial bodies and also in near-Earth asteroids.

Near Earth Asteroids are poorly explored but provide unique information concerning the evolution of our Solar System as well as the early development of life (e.g. Lühr et al 2018). The characterization of these bodies will allow to obtain information on the ancient history of the Solar System. Such topics cannot be addressed through missions to larger and evolved planetary bodies since their surface have been intensively shaped by endogenic and exogenic processes throughout billions of years. Questions, as if the bodies are agglutinated remnants of the primitive matter or if they are debris of other more or less differentiated bodies, can help to understand formation and differentiation processes in the origin and evolution of the universe.

Surfaces of Near Earth Objectives (e.g. asteroids) and celestial bodies are often composed of rocks of accumulated rock fragments of primordial and/or magmatic origin and they are usually covered with regolith. To investigate the origin of such distinct silicate- and iron-bearing rocks in the planetary context as well as their differentiation and alteration processes, it is necessary to perform an exhaustive in-situ characterization of the surface. To that purpose, the NEWTON consortium is pushing new projects concerning the development of a synergetic suite of instruments (X-ray fluorescence device, Infrared and Mössbauer spectrometers, NEWTON instrument to measure the susceptibility and a magnetometer).

In the context of such initiatives NEWTON project members propose that NEWTON instrument may have a key role, since intensities of the magnetic susceptibility as well as remanence and the magnetic orientation will be able to indicate the magnetization history and intensity of the original dynamo source in the case of objects split from evolved bodies (e.g. Lühr et al. 2018). It has also to be taken into account that so far the fly-byes around asteroids have permitted to measure only very low magnetic signatures (TABLE 2 and e.g. Auster et al. 2015), which leaves the in-situ investigations as a very important future tool.

TABLE 2. First Magnetic field measurements of asteroids (Lühr et al 2018).

Table 1 Data used from Kivelson et al. (1993), Richter et al. (2001, 2012), Auster et al. (2010), Acuña et al. (2002), Coradini et al. (2011), McCoy et al. (2001). The magnetization values for simplicity show orders of magnitude only

Asteroid	Gaspra	Braille	Šteins	Lutetia	Eros
Mean radius [km]	7	0.8	3	49	9
Density [kg/m^3]	4000	3900	3200	3400	2650
Material	Metal Olivine Pyroxene	Basalt Olivine Pyroxene	Enstatite	Chondrites Enstatite	Chondrites Achondrites
Fly-by	29.10.1991	29.7.1999	5.9.2008	10.7.2010	12.2.2001
CA [km]	1600	28	799	3120	landing
Measured field [nT]	draping	2	< 1	< 1	< 5
Estimated values					
Dipole moment [Am^2]	$\sim 10^{13}$	$\sim 10^{11}$	$< 10^{12}$	$< 10^{12}$	$< 10^{10}$
Spec. moment [Am^2/kg]	$\sim 10^{-2}$	$\sim 10^{-2}$	$< 10^{-3}$	$< 10^{-7}$	$< 10^{-6}$

Some asteroid missions which will be launched after 2020 are recently at an early planning stage:

Discovery missions:

- Psyche orbiter will travel and study the asteroid 16 Psyche, the most massive metallic asteroid in the asteroid belt, thought to be the exposed iron core of a protoplanet. The launch is planned for 2022. It will probably carry an imager, a magnetometer, and a gamma-ray spectrometer.
- LUCY: Named after the hominin Lucy, it will tour six Trojan asteroids in order to better understand the formation and evolution of the Solar System. The launch is planned for 2021. It will arrive at Jupiter's L4 Trojan cloud in 2027 to visit 3548 Eurybates, 15094 Polymele, 11351 Leucus, and 21900 Orus. After an Earth flyby, Lucy will arrive at the L5 Trojan cloud (trails behind Jupiter) to visit the 617 Patroclus–Menoetius binary in 2033. It will also fly by the inner main-belt asteroid 52246 Donaldjohanson in 2025

New Frontiers missions:

- Among the NASA´s New Frontier missions are the "COmet Nucleus Dust and Organics Return" (CONDOR) and CORSAIR comet sample return
- CHINA: currently in their planning phases, are a comet/asteroid sample-return mission

3. ANALYSIS / RESULTS OBTAINED FROM PROSPECTION CAMPAIGNS

3.1. The origin of extreme high magnetic anomalies: case study at a volcanic spatter cone from Pali Aike volcanic field, southernmost Chile

First applications of components of NEWTON instrument have been performed during magnetic mapping of an agglutinated spatter cone of the Pali Aike volcanic field where our previous studies revealed extraordinary high magnetic anomalies in the range of +6000 to +8000 nT (FIGURE 3; Diaz-Michelena et al. 2016). However, the reasons for this very pronounced anomaly remained obscure. Thus, we have performed a detailed electron microprobe study within the frame of NEWTON project to investigate the magnetic carriers and the single versus multi-domain status. These results indicate that redox-sensible alteration process along the crater walls caused an alteration of olivine in the basalt and let to the formation of many additional single domain magnetites (see back scatter electron images of FIGURE 4). They have the capacity to carry a strong remanent magnetic signature. This is a very important result since it could explain strong local variations in the magnetic signature of basaltic rocks on planetary surfaces. These new results have been also described in the D2.2 report and in an EGU poster. During 2018 we have written a manuscript for an International Journal which will be submitted in Nov. 2018 (Kilian et al. 2018). Due to these very interesting results we have performed a further magnetic field campaign at volcanic craters of Lanzarote which are described in the next chapter 3.2.

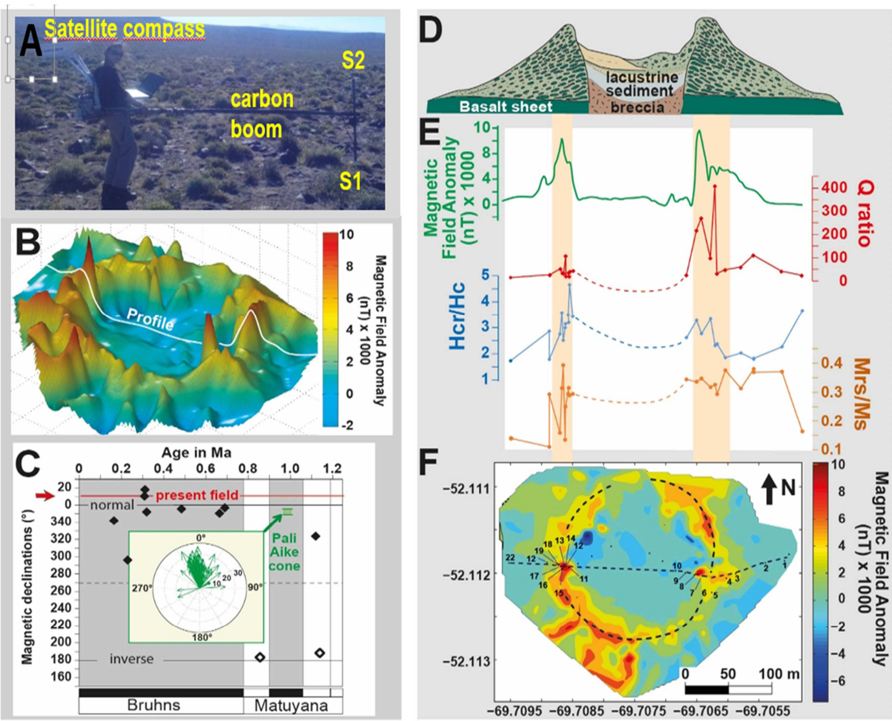

FIGURE 3. Magnetic mapping in and around a magnetic spatter cone in the Pali Aike Volcanic Field, Chile (Diaz-Michelena et al 2016). A: Measurement system with carbon boom and two sensors (S1 and S2) as well as georeferenciation and attitude systems with a satellite compass; B: 3-D crater view with the magnetic anomalies centred along the crater wall; C: Magnetic declination with paleomagnetic components due to very strong remanence of the basaltic rocks; D: Schematic geological profile across the carter; E: Distinct magnetic properties of representative rock samples along a transect across the crater and F: Magnetic map of the crater and sampling locations.

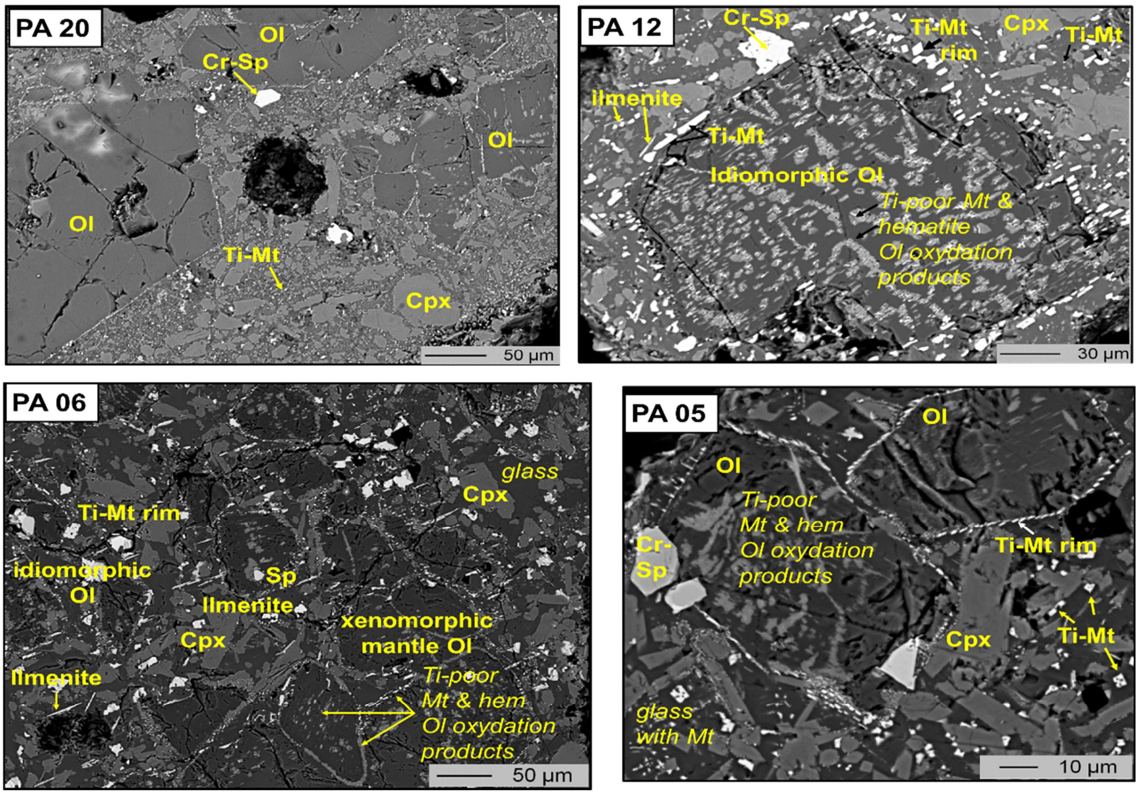

FIGURE 4. Back scatter electron images of basaltic rocks from the investigated volcanic spatter cone within the Pali Aike Volcanic field. The light grey tiny minerals within the olivines represent cryptocrystalline mixtures of magnetite and partly hematite formed by redox-sensible alterations. They are much more frequent in samples next to the crater wall (e.g. PA12 and PA 5) where the pronounced magnetic anomaly appears and less abundant in a sample from the outermost slopes of the cone where lower magnetic signatures are evident (PA 20).

3.2. Magnetic signatures of craters within the Lanzarote Volcanic Field

We have performed first magnetic mapping tracks at three volcanic craters within the recent (1834) basaltic volcanic fields of Lanzarote. The aim was to investigate if these carters also have such extreme magnetic anomalies as we discovered along the crater rim of a Pali Aike volcanic spatter cone, and if this is a more common planetary surface phenomena. First results of the magnetic signatures are shown in FIGURE 5 and they indicate partly pronounced magnetic anomalies centred along the crater rim as documented from a Pali Aike crater in FIGURE 3. A more detailed mapping is pending, since the mapping along the steep slopes and across partly unstable large lava blocks is difficult and dangerous. Thus a drone-based magnetic survey is foreseen, using components of NEWTON system.

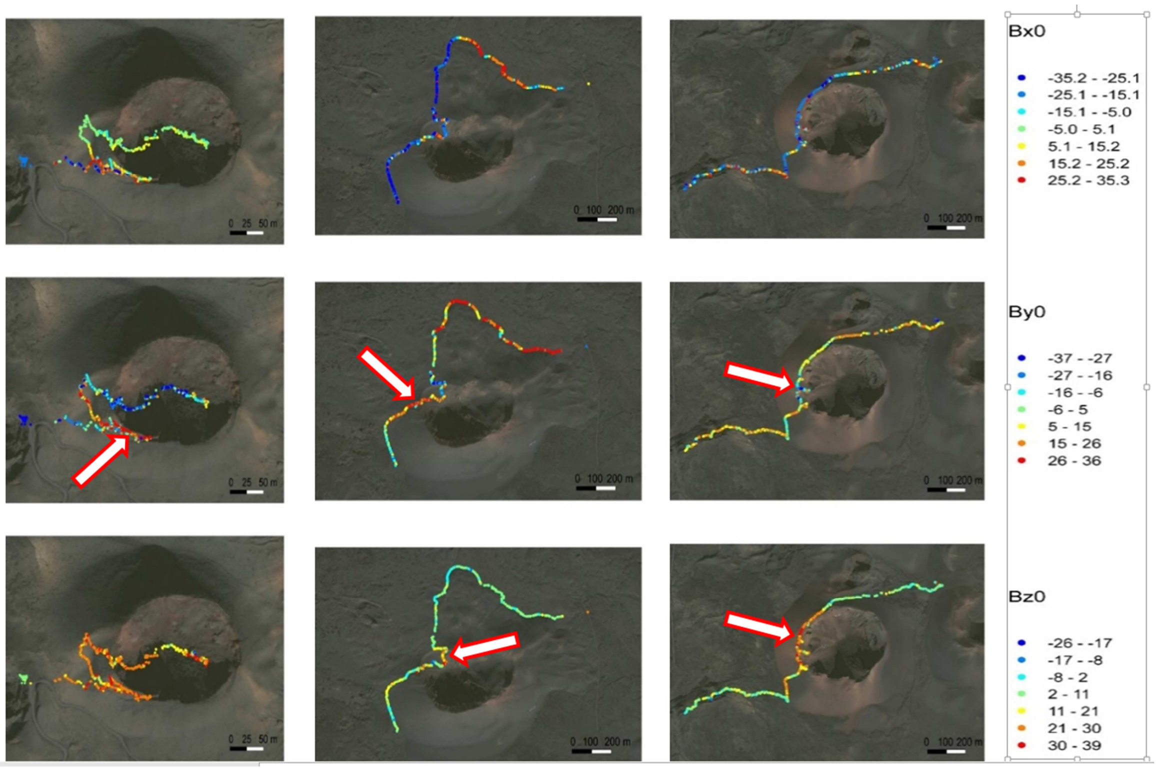

FIGURE 5. Vector magnetic components measured along selected volcanic crater cones of Lanzarote. The tracks include the carter rims and partly cross from inside towards the outer slopes of the crater. Red arrows indicate areas with magnetic anomalies which are located especially along the carter rims.

3.3. Crater formation scenarios within basaltic planetary rock surface: Case study of the origin of an impact-like crater on the Barda Negra Plateau, Neuquen, Argentina

On Earth and other celestial bodies, simple type craters with diameters of several hundred meters up to a few kilometres represent a very common feature (FIGURE. 6 and 11). In general, they can be formed by meteorite impacts (e.g. Osinski & Pierazzo 2013; Kenkmann et al. 2017) or by explosive volcanism (e.g. Seib et al. 2013; White & Ross 2011). However, since crater rims may be more or less eroded and the sedimentary infill of the crater is often not well exposed, the morphological features alone may not be indicative for their origin and this leads often to a scientific controversy regarding the possible formation scenarios. Both above-mentioned high energy crater types are characterized originally by more or less elevated rims compared to surrounding basement or target rocks. Their crater rims are typically composed of ejected clastic crustal rock fragments which may include pyroclastic volcanic or impact melt/glass remnants and/or components of the collided meteorite. But such features are missing at the Barda Negra crater. Additionally, planetary surfaces may be shaped by chemical dissolution of underlying crustal units (e.g. carbonate, gypsum or ice-bearing rocks; e.g. Gutiérrez et al. 2014 and 2016) and this could form deep crater-like circular depressions Such karst-like structures are named pits or sinkholes and sometimes their morphologies resemble the above described high energy craters. Recently such morphological features have also been described from the comet 67P (Vincent et al. 2015) and from some areas on Mars (Adams et al 2009, Tichy 2009). In both cases, sinkhole formations were suggested to be due to dissolution of not exposed ice or evaporitic sediments.

NEWTON investigation of the Barda Negra crater (FIGURES 6 to 9) represents a novel case study which highlights, that some craters with impact-like morphologies could have been also form by subsidence processes. Below is given the abstract which is being prepared regarding this work.

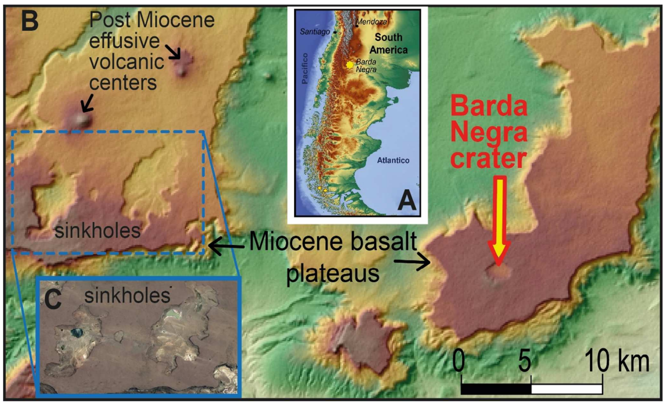

FIGURE 6. (A and B) The Barda Negra crater on Miocene Plateau basalts**. C:** Sinkhole-like structures are evident on the eastern Plateau basalts.

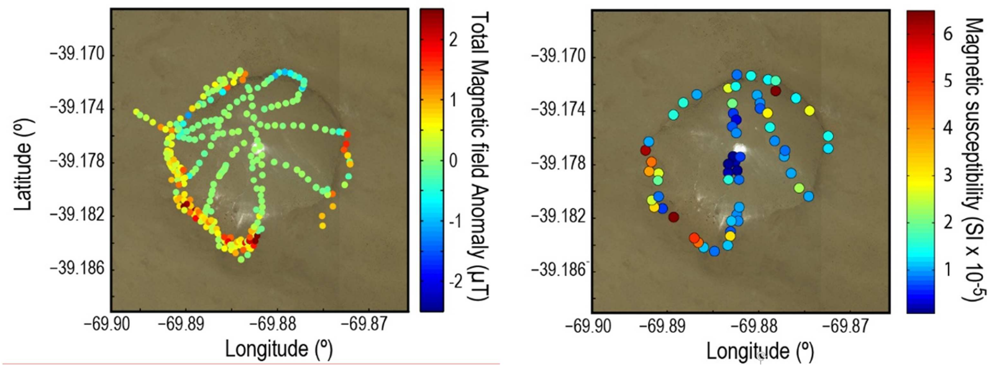

FIGURE 7. Magnetic field anomalies and susceptibilities in and around the Barda Negra crater, Nequen, Argentina. **Left:** Total magnetic field anomalies in µT within and around the crater. **Right:** Overall magnetic susceptibilities of the sedimentary infill compared to the plateau basalts of the crater rim.

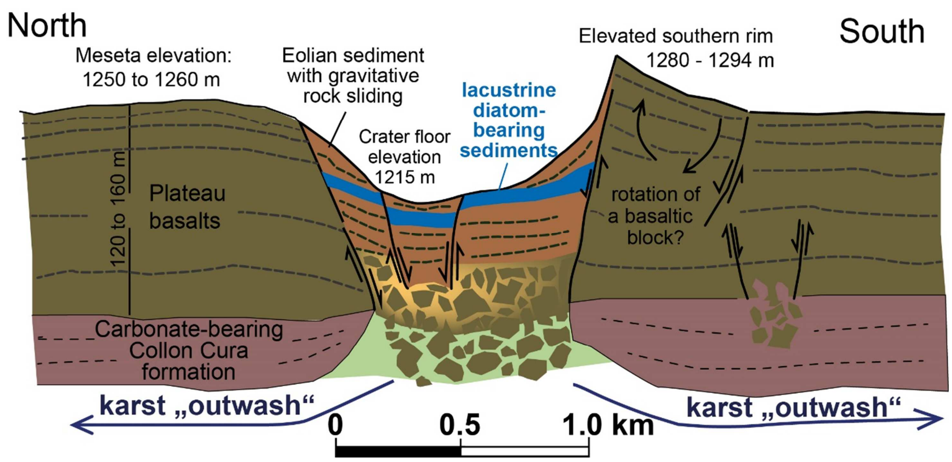

FIGURE 8. North-South cross-section of Barda Negra crater illustrating the sinkhole formation within the 120 to 160 m thick plateau basalts and the karst-like outwash of carbonates from the underlying Collón Curá formation.

The formation of a giant collapse caprock sinkhole on the Barda Negra plateau basalts (Argentina): magnetic, mineralogical, tectonic and geomorphological evidences

Diaz-Michelena, M., Kilian, R., Acevedo, R. D., Baeza, O., Langlais, B., Mesa, J.L., Rios, F., Rocca, M. & Veracruz, J.

Abstract

Based on remote sensing exploration a 1.5 km wide and 40 m deep crater-like structure within the 10 Ma old Barda Negra basaltic plateau, located 35 km to the South of the town Zapala in Argentina, was described as likely meteorite impact crater, due to very similar morphological characteristics compared to the Barringer crater in Arizona. In contrast to these previous findings, our field work in this circular depression did not reveal raised rims around it which are typically formed by ejected clastic crustal rock fragments in the case of either a phreatomagmatic eruption (maar-like origin)or a meteorite impact. Furthermore, mineralogical investigations of rocks and sediments do not show any high PT minerals, like coesite or stishovite, or remnants of an impactite or impact melt/glass. There are also no textural evidences in minerals and rocks for impact-related fracturing or stress. A detailed geotectonic mapping indicates a successive crater development which invokes local stepwise subsidence consistent with a sinkhole origin. Remote sensing data also show up to 100 m deep sinkholes with large dimensions of 3 x 6 km within a cogenetic neighboring basaltic plateau with similar lithologies, located 20 km westward of the Barda Negra. Magnetic mapping with the new EU-funded NEWTON multi-sensor instrument shows a 1000 to 3000 nT lower magnetic signature within the crater compared to its basaltic rims and surrounding plateau basalts, consistent with collapsed basalts underlying a 20 to 25 m thick sedimentary crater infill with very low magnetic susceptibilities. Below the 120 to 160 thick basaltic plateau lava sheet, the 60 to 70 m thick and 14 to 15 Ma old carbonate-bearing Collón Curá formation represents ideal rocks for dissolution and karst formation. The giant collapse sinkholes of up to 6 km in diameter within caprocks of very thick plateau basalts represents unique examples for planetary surface shaping processes which also occurs on Mars or comets in areas with basalts or rigid caprocks.

3.4. Magnetic mapping of very low magnetic contrast between differentiated andesites of La Gata volcanic province (Spain) and associated coastal marine sediments

Miocene andesitic and dacitic volcanic rocks from the La Gata volcanic Province in Southern Spain are associated with Messinian litoral sediments of biogenic, evaporitic and siliciclastic compositions. Such rocks have only a limited amount of magnetite (its only magnetic carrier) and thus the magnetic contrast between the different formations is only week. However, our first mapping results indicate that NEWTON instrument was able to differentiate between the above described rock types by its magnetic anomalies in the range of +50 to +700 nT. This is show in FIGURE 9 from one of our mapping sites.

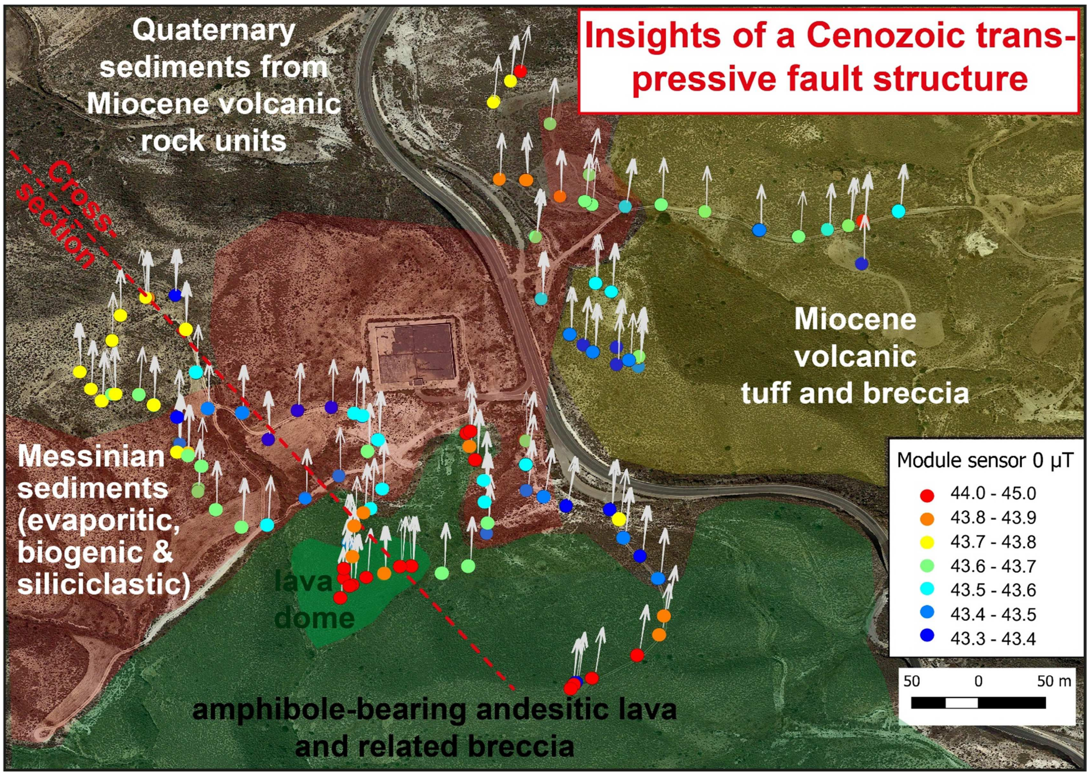

FIGURE 9. Example of NEWTON vector magnetic mapping of Miocene andesitic pyroclastic rocks and a volcanic lava dome as well as Messinian evaporitic, biogenic and siliciclastic sediment types. Their magnetic contrast is in the range of +50 to +700 nT.

3.5. Magnetic tracing of hydrothermal mineralization processes: El Laco and Rio Tinto

Most hydrothermal mineralizations are associated to magmatic processes and formation of magnetic carriers. They represent a very common feature on Earth as well as Mars and other celestial bodies (e.g. Ovalle et al. 2018; Black & Hynek 2017). Deeper crustal fracture zones often enable water pathways and thus associated multiple mineralization processes. However, they can be also related to larger impacts (Osienski & Pierazzo 2013).

The most extended local magnetic anomaly on Earth is formed by magnetite-rich bodies at El Laco volcano in Chile where we have tested magnetic devices under extreme environment conditions and within an extraordinary magnetic range (Diaz-Michelena et al. 2016). The El Laco magnetites were formed by hydrothermal processes around this dacitic volcano (e.g. Ovalle et al. 2018; Tornos et al 2017) and they also represent a possible scenario to explain extremely pronounced magnetic anomaly on terrestrial bodies.

Besides magnetite, pyrrhotite is an important magnetic carrier which is often formed by hydrothermal mineralizations. Thus it is an important magnetic tracer for gold and copper-bearing ore deposits (e.g. Diaz-Michelena & Kilian 2015).The Varszican Pyrite belt represents the most important European resource of such hydrothermal ore deposits. The mineralization was often accompanied by some pyrrhotite formation. Since very few or no magnetic mapping have been previously done in most mineralization areas, we have performed a high resolution mapping along the Rio Odiel, which cross-cuts the Varsician lithological units (Yesares et al. 2017). Mapping results with NEWTON instrument clearly depict several pyrrhotite-bearing hydrothermal mineralization zones by magnetic anomalies of > 100 nT as shown in FIGURE 10. These results highlight the potential of NEWTON instrument to detect hydrothermal mineralization and ore deposits.

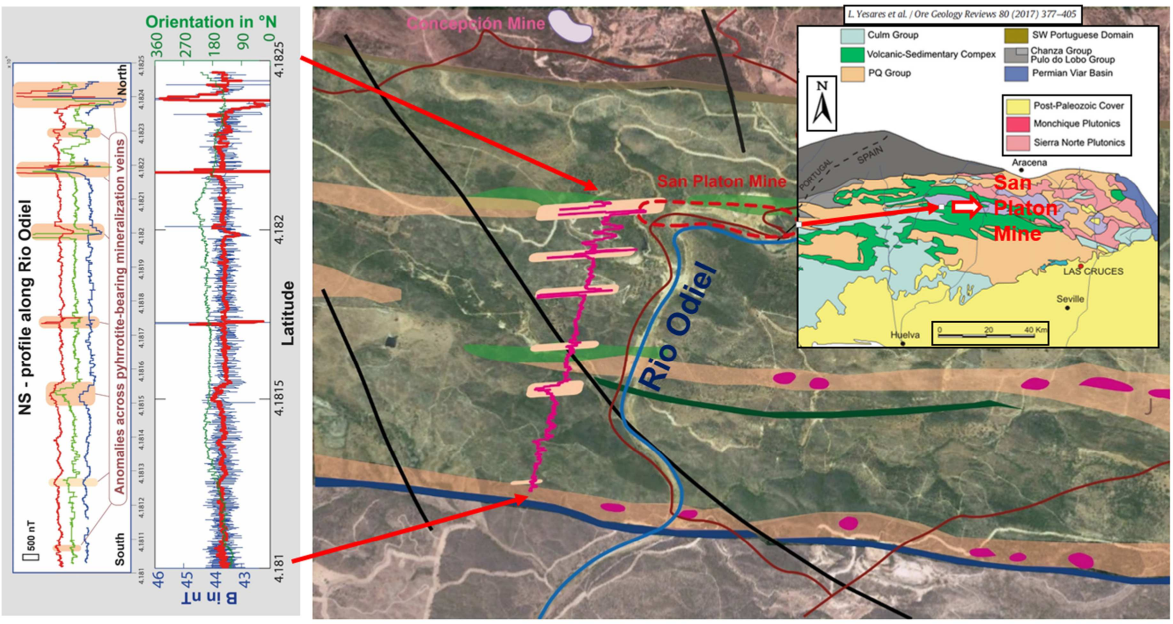

FIGURE 10. High resolution magnetic mapping along the Rio Odiel, river cross-cutting the Variszican lithological units from North to South. The three tracks show clearly detectable positive magnetic anomalies which are caused by pyrrhotite-bearing hydrothermal mineralization zones. The northernmost concerns to the inactive old San Platon Mine.

4. IMPROVEMENT OF MAGNETIC MODELLING OF REMOTE SENSING DATA FROM CELESTIAL BODIES WITH IMPLICATION FOR LANDING SITE SELECTION

Orbital magnetic mapping of surface magnetic characteristics of the Mars and Moon or other celestial bodies (Langlais et al 2004) only provide very low spatial resolution. Depending on altitudes of the orbital magnetic mapping, model-based data extrapolations towards the planetary surface are integrating areas of thousands of square-kilometres. Since direct measurements on the surface are missing, in general the real magnetic intensities on the surface rocks depend on the used model parameters. The terrestrial examples of Pali Aike volcanic rocks (Chapter 3.1) show magnetic anomalies of up to 8000 nT within several meters, as well as the magnetite-bearing bodies of El Laco document anomalies of >50000 nT within less of 50 m distances (Diaz-Michelena et al 2016). However, aeromagnetic data from both terrestrial sites, obtained from low altitudes (500 to 100m above the ground), only depict anomalies of <50 nT. Despite this general problematic of remote sensing magnetic data extrapolation there have been recently several working groups which try to establish improved models for a better spatial data resolution and estimates of averaged surface magnetic properties. A relatively good high resolution model was recently presented by Tsunakawa et al. (2015) for the Moon. This was already presented in the D2.2 Report. Below we summarize some results of a German (Morschhauser et al. 2018) and French Research Group obtained with NEWTON project (Langlais et al 2018).

4.1. Modelling of martian magnetic signature by Morschhauser et al. 2018

A spherical harmonic model of the crustal magnetic field have been derived by Morschhauser et al. (2014) and (2018) from satellite vector magnetometer data. This model allows to study the crustal magnetic field at relatively high resolution down to surface altitudes as the examples of FIGURE 11 A and 11 B. Based on this model, the required magnetization of the Martian crust for the observed southern hemispheric anomalies are discussed as well as the possible demagnetization in the areas of impact craters, as well as the low or missing magnetic signatures in volcanic fields is discussed by the authors. Furthermore synthetic tests were used to constrain paleopole positions from satellite measurements.

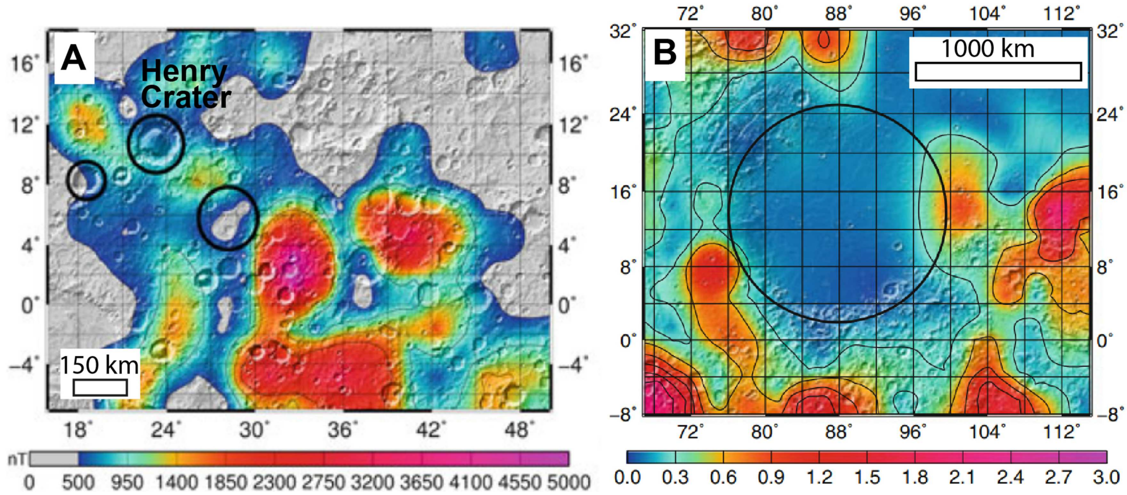

FIGURE 11. (A): The intensity of the lithospheric magnetic field model of Morschhauser et al. (2014) over a selected region, plotted at the mean surface altitude of 3393.5 km. Black circles highlight impact craters that differ in their lithospheric magnetic field signatures and visible magnetizations. (B): Visible magnetization, I, in A/m, over the region in and around the 1200 km wide Isidis impact basin (Projection is Mercator) indicating impact-related demagnetization (Morschauser et al. 2018).

4.2. Improved modelling of magnetic intensities on the Martian surface (NEWTON Project)

In the frame of NEWTON project, Benoit Langlais and his working group has developed a new model of the Martian magnetic field, in order to improve estimates concerning the magnetic field intensities at the Martian surface. This work was recently submitted for publication. The abstract of the publication (under review) is reproduced here:

While devoid of an active magnetic field today, Mars possesses a remanent magnetic field which may reach several thousand nT locally. The exact origin, and the events which have shaped the crustal magnetization remain largely enigmatic. Three magnetic field datasets from two spacecraft collected over 13 cumulative years have sampled the martian magnetic field over a range of altitudes from 90 km up to 6000 km: a- Mars Global Surveyor (MGS) magnetometer (1997-2006); b- MGS Electron Reflectometer (1999-200-); c- MAVEN magetometer (2014-today). In this paper we combine these complementary datasets for the first time to build a new model of the Martian internal magnetic field. This new model improves upon previous ones in several aspects: comprehensive data coverage; refined data selection scheme: modified modeling scheme; discrete-to-continuous transformation of the model; increased model resolution. The new model has a spatial resolution of ~ 160 km at the surface, corresponding the spherical harmonic degree 134. It shows small scales and well defined features, which can now be associated with geological signatures.

This new model builds up on an updated modeling scheme originally developed in Langlais et al. (2004). In addition it benefits from additional measurements by MAVEN, carefully (re)selected magnetic field by MGS, and estimates of the total field by Electron Reflectometry. We now reach a lateral resolution of 160 km, and can downward continue the model to the Martian surface.

Thanks to this model, we can now predict the magnetic field intensities that landed instrument suites (such as NEWTON) would sense. For many reasons (mainly aerodynamics) all the lower plains within a (large) equatorial band are potential landing site. Here we illustrate what our model can achieve by plotting the magnetic field map over the landing site of InSight, a NASA mission which is planned to land on Mars late November 2018.

InSight carries a seismometer experiment suite designed to detect and record possible Mars quakes. The main objective is to study the internal structure of the planet. The landing site is within Elysium Planitia, to the South-West of Elysium. We show in FIGURE 12 the predicted magnetic field components. Although the lateral resolution of the model is larger than (for instance) the lateral extent of the landing ellipse (about 120 km), the model shows very important changes. For instance, the total field varies from about 280 nT to the east to 380 to the west.

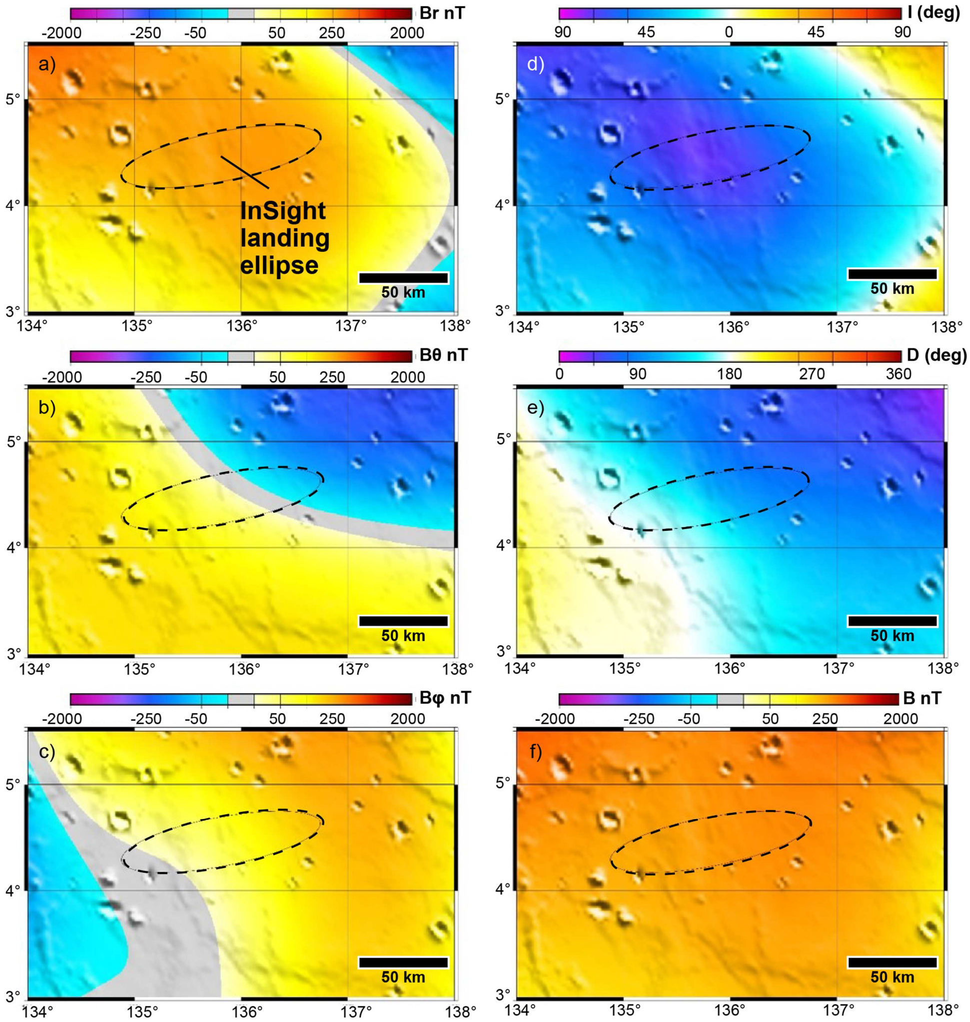

FIGURE 12. Predicted magnetic field components in the vicinity of the InSight landing site (shown with the elongated ellipse). From top to bottom and left to right, Br radial Bθ, horizontal south, Bφ horizontal east, Inclination, Declination and Total field. Predictions by the model of Langlais et al. (2018).

5. UPDATED TECHNICAL SPECIFIATIONS FOR NEWTON INSTRUMENT

5.1. NEWTON Prototype 1

Mars and moon scenarios are highly demanding terrains for surface instrumentation in terms of hardware requirements. NEWTON prototype 1 is intended to operate in such environments, and to verify the reliability of the instrument, the most critical parts (sensor head) had been subjected to environmental tests, e.g. vibration and thermal-vacuum test, where structural integrity and operation performance where verified. The results for these tests are presented in D3.4.

The levels of the thermal-vacuum and vibration tests where copied from requirements for AMR instrument on board ExoMars 2020 mission, an instrument with requirements for the Martian atmosphere in a landing mission. For more details about the test levels, see Annex 1.

The electronics are developed with space qualified components, or failing them, with components which have equivalents with space qualification, so for an FM development these non-qualified parts must be replaced with space-qualified parts.

The magnetometer is based on AMR technology, and INTA partner is developing in parallel to this project the AMR instrument, a Flight Model magnetometer based on equivalent COTS AMR magnetometers that can be used in a Flight Model version of the NEWTON prototype 1 in future occasions.

The specific qualification campaign for the instrument is to be defined as a function of the flying opportunities, depending on many circumstantial factors such as: launcher rocket type, season and geographic coordinates for launch, target space body, geological location for landing, mission duration, mission phases, space flight duration and conditions, space platform characteristics, and many others.

The TRL 6 expected for NEWTON prototype 1 will prove that the instrument is ready to perform properly under standard space environmental conditions, as already done on the environmental tests, and that the instrument has performed correctly in terrestrial analogues after field campaigns foreseen in Work Package 5.

5.2. NEWTON Prototype3

The NEWTON instrument prototype 3 is designed to perform measurements of samples commonly used in geological prospections. Sample geometry is usually cylindrical with typical dimensions around 2 cm diameter and 2 cm length. The expected measurements are low frequency susceptibility (DC- 1KHz), magnetization curves (DC-1KHz) and high frequency susceptibility (1KHz-100KHz).

The prototype 3 requires sample preparation and its dimensions and performances conditions require of a high dimensions’ rover with more specific characteristics, structure and support devices; or to be part of a manned landing mission or based station where a human could manipulate the samples and the device.

Within the frame of the NEWTON project, the target for prototype 3 is to have a laboratory device for geological samples characterization, and demonstrate the validity and reliability of the results obtained with this new technology, which is of high interest for future in-situ characterization.

6. SUMMARY AND CONCLUSIONS

The roadmap of the future space exploration programs has been reviewed and included in this document. NEWTON technology provides significant advances in the field of the magnetic extraterrestrial characterization which can be applied in future long-term space exploration missions for the understanding of key questions in the Solar System exploration. The present and future (expected) roadmaps of the ESA and NASA clearly point to the Moon exploration. For this scenario NEWTON instrument can be a very good candidate for future missions. In the same way, Mars is a key scenario for the application of NEWTON technology, although at the moment, there does not seem to be any near future mission to Mars provided with lander.

The aims of future space missions' programs mainly concern a better understanding of the origin and geological history of the celestial bodies as well as their magnetization histories. It is expected that future missions will also investigate elemental enrichment processes and related formation of extraterrestrial resources and ore deposits. With this regard, NEWTON technology can significantly contribute to the achievement of these objectives by means of tacking part of advanced multi-instrument suites which perform a complete in-situ characterization. In this context of more extended multi-instruments applications, NEWTON technology can be applied to the exploration of other celestial bodies such as Near Earth Asteroids. Near Earth Asteroids are poorly explored but their characterization can provide unique information concerning the evolution of our Solar System as well as the early development of life.

This report also provides the results gained from the first tests performed to the NEWTON instrument on many distinct terrestrial analogues. This field work allows to proof the capacity of NEWTON for geophysical exploration in the context of future exploration missions, as well as to improve out data interpretation capabilities and magnetic models.

In addition to this, NEWTON instrument has been subjected to standard space environmental conditions, i.e. vibration and thermal-vacuum tests, in order to verify the reliability of the most critical parts of the instrument, i.e. sensor head, to operate under these highly demanding scenarios which also demonstrate the capacity of NEWTON to be part of future space exploration programs.

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ANNEX 1: Vibration and Thermal Vacuum test levels

All tests performed to the NEWTON prototype's sensor head had follow the European standard: ECSS-E-ST-10-03C Testing. The vibration tests have been performed at INTA facilities, following the levels stated for AMR instrument, to be part of the ExoMars 2020 mission to Mars planet.

The following table describes the levels for the mechanical vibration tests performed to the NEWTON prototype 1:

TABLE 3. Vibration levels for the mechanical vibration tests performed to the NEWTON instrument prototype 1.

VIBRATION LEVELS	Low-sine sweep: 5Hz to 2000 Hz at 2 oct / min 0.5g for each axis **TBC** Sine: 5Hz to 200 Hz at 2 oct / min 1.5g for each axis **TBC** Random: $f < 100$ Hz $0.04g^2$/Hz **TBC** Random: $f = 200 - 500$ Hz $0.1g^2$/Hz **TBC** Random: $f = 2$ kHz $0.026g^2$/Hz **TBC** *Log ramps between those ranges* The instrument must not have resonant frequencies less than 40 Hz.

The thermal-vacuum tests have been performed at INTA facilities, following the levels stated for AMR instrument, to be part of the ExoMars 2020 mission to Mars planet. The test consisted of the application of four thermal cycles as represented in the following image under high vacuum conditions.

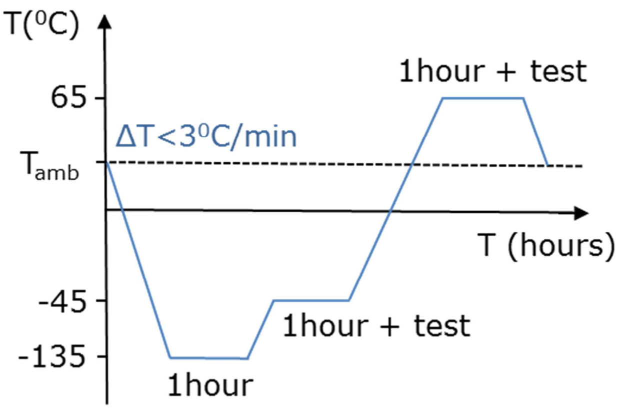

FIGURE 13. Thermal cycles for the thermal-vacuum tests.

These tests were performed with a pressure <10-5 mbar (typically ~$1\text{-}2\cdot10^{-6}$ mbar), combining storage (-135 ºC) and operating (-45ºC and 65ºC) temperatures. At the operating temperatures, the NEWTON instrument was turned on and an ad-hoc developed reference sample for these tests was measured to verify correct performance at the Martian expected operation temperatures. The complete tests performed to NEWTON instrument prototype 1 can be found in deliverable D2.3.